Neutrino Factories

1. Physics Motivation
2. Design and R&D Status
3. Main Challenge and Prospects
4. Opportunities

Long-baseline goals: What is NOT known

1. Does three-flavor mixing provide the right framework or are there contributions from: additional (sterile) neutrinos, neutrino decay, CPT-Violation, extra dimensions, …?
2. Is $\sin^2 2\theta_{13}$ small or tiny (or zero) ?
3. Is δ non-zero (Is there CP-violation in the lepton sector, and does it contribute significantly to Baryogenesis via Leptogenesis) ?
4. What is the sign of Δm_{32}^2 (pattern of neutrino masses) ?
5. Is $\sin^2 2\theta_{23}$ maximal (= 1) ?

The answers to these questions may lead us towards an understanding of the origin of flavor … but getting the answers will require the right tools.

Getting answers to the basic questions will not be easy

The key oscillation mode that must be measured to determine $\sin^2 2\theta_{13}$, the sign of Δm_{32}^2, and δ_{CP} is $\nu_\mu \to \nu_e$, which has not yet been observed. We know the oscillation amplitude for this mode is small, at most a few x 10^{-2}.

Conventional neutrino beams can only access $\nu_\mu \to \nu_e$, for which the background levels are about 10^{-2} of the total event sample. Hence, the signal/background ratio is at most a few $\times$ unity (if the oscillation amplitude is just below the present bound), and is likely to be much less than unity.

The oscillation probabilities depend in a complicated way on the oscillation parameters. Extracting unique parameter values and rigorously testing the oscillation framework will be challenging.

Oscillation Probabilities

- $\Delta = \Delta m^2_{31} L/4E$
- **qualitative understanding** $\Rightarrow$ **expand in** $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ **and** $\sin^2 2\theta_{13}$
- **matter effects** $\hat{A} = A/\Delta m^2_{31} = 2VE/\Delta m^2_{31}; \;\; V = \sqrt{2} G_F n_e$

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\Delta + 2\,\alpha\,\cos^2\theta_{13}\cos^2\theta_{12}\sin^2 2\theta_{23}\Delta\cos\Delta$$

$$\begin{aligned} P(\nu_e \to \nu_\mu) \approx\ & \sin^2 2\theta_{13}\sin^2\theta_{23}\frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} \\ & \pm \sin\delta_{CP}\,\alpha\sin 2\theta_{12}\cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{23}\sin(\Delta)\frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\ & + \cos\delta_{CP}\,\alpha\sin 2\theta_{12}\cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{23}\cos(\Delta)\frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\ & + \alpha^2\sin^2 2\theta_{12}\cos^2\theta_{23}\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2} \end{aligned}$$

□
□

Note: (i) For □□ □, A □ -A, (ii) The sign of A depends on the sign of □m_{32}^2

Beam Properties at a Neutrino Factory - 1

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \Rightarrow 50\%\ \nu_e\ ,\ 50\%\ \bar{\nu}_\mu$$

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu \Rightarrow 50\%\ \bar{\nu}_e\ ,\ 50\%\ \nu_\mu$$

Decay kinematics well known $\Rightarrow$ minimal systematic uncertainties in spectrum, flux, & comparison of neutrino with antineutrino results.

ν_μ flux at 20 GeV NuFact with 2×10^{20} useful decays/yr is comparable to a Superbeam with 10 $\times$ the NuMI flux. At higher energies NuFact event rates ~E^3.

The ν_μ spectrum does not have a high energy tail … which is a source of background for conventional ν_μ beams.

Electron Neutrinos & Wrong-Sign Muons

The primary motivation for interest in neutrino factories is that they provide electron neutrinos (antineutrinos) in addition to muon anti-neutrinos (neutrinos). This enables a sensitive search for $\nu_e \to \nu_\mu$ oscillations.

$$\mu^+ \to e^+ \, \nu_e \, \bar{\nu}_\mu \xrightarrow{CC} \mu^+$$
$$\downarrow$$
$$\nu_\mu \xrightarrow[CC]{} \mu^-$$

$\nu_e \to \nu_\mu$ oscillations at a neutrino factory result in the appearance of a "wrong-sign" muon … one with opposite charge to those stored in the ring:

Backgrounds to the detection of a wrong-sign muon are expected to be at the 10^{-4} level $\Rightarrow$ $\nu_e \to \nu_\mu$ oscillations with amplitudes as small as $O(10^{-4})$ can be measured !

Signal Rates & Signal/Background

Note: backgrounds for $\nu_e \rightarrow \nu_\mu$ measurements (wrong-sign muon appearance) are much easier to suppress than backgrounds to $\nu_\mu \rightarrow \nu_e$ measurements (electron appearance).

Many groups have calculated signal & background rates. Recent example
Huber, Lindner & Winter; hep-ph/0204352

JHF-SK: Beam = 0.75 MW, M_{fid} = 22.5 kt, T = 5 yrs
JHF-HK: Beam = 4 MW, M_{fid} = 1000 kt, T = 8 yrs
Entry-Level NUFACT: Beam = 1×10^{19} decays/yr, M_{fid} = 100 kt, T = 5 yrs
High-Performance NUFACT: Beam = 2.6×10^{20} decays/yr, M_{fid} = 100 kt, T = 8 yrs

$\Delta m_{32}^2 = 0.003\ \mathrm{eV}^2$, $\Delta m_{21}^2 = 3.7\times10^{-5}\ \mathrm{eV}^2$, $\sin^2 2\theta_{23} = 1$, $\sin^2 2\theta_{13} = 0.1$, $\sin^2 2\theta_{12} = 0.8$, $\delta = 0$

	Superbeams		Neutrino Factories	
	JHF-SK	JHF-HK	Entry Level	High Performance
Signal	140	13000	1500	65000
Background	23	2200	4.2	180
S/B	6		360	

Oscillation Measurements at a Neutrino Factory

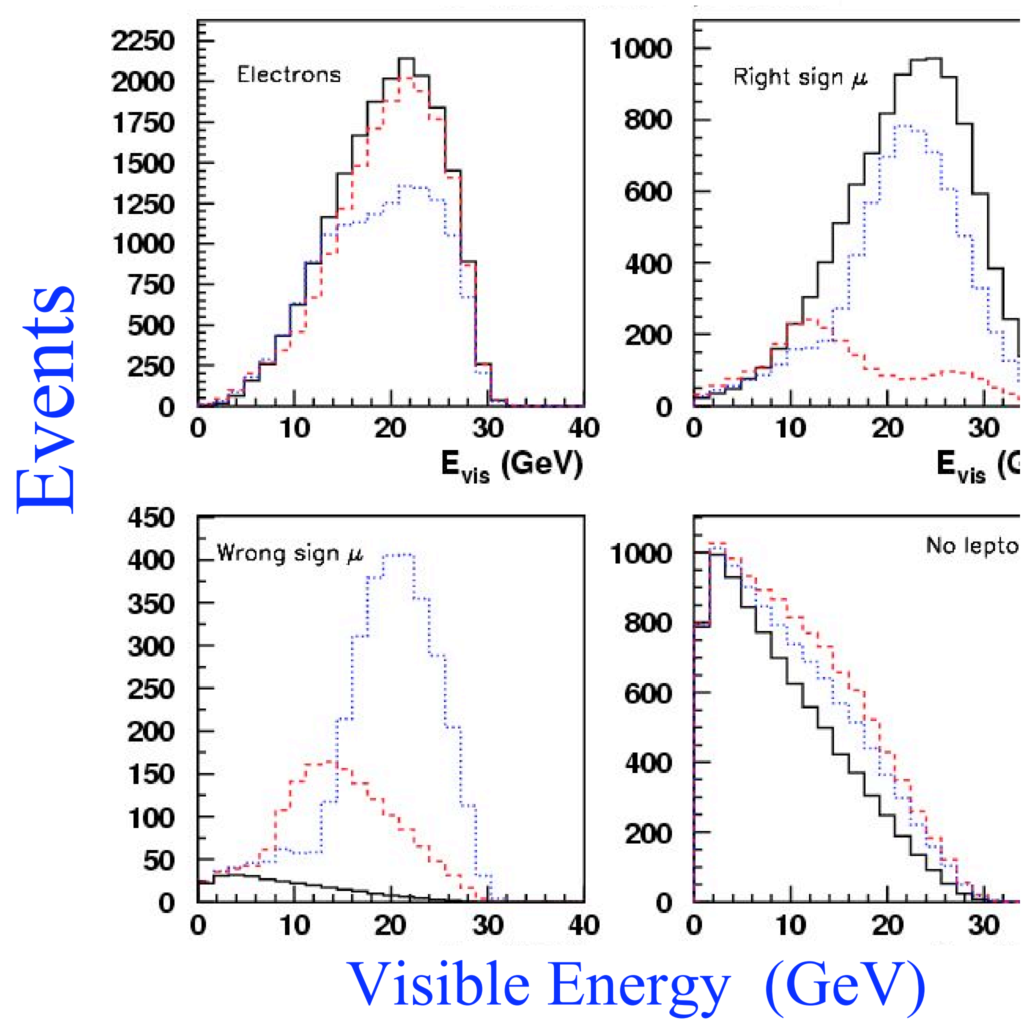
There is a wealth of information that can be used at a neutrino factory. Oscillation parameters can be extracted using events tagged by:

a) right-sign muons
b) wrong-sign muons
c) electrons/positrons
d) positive τ-leptons
e) negative τ-leptons
f) no leptons

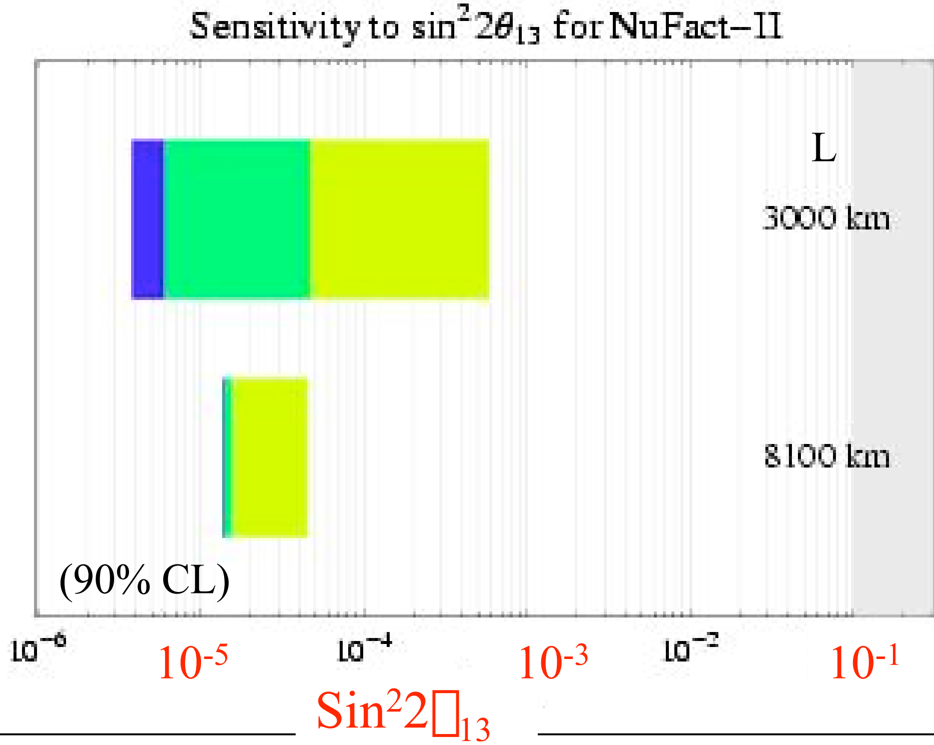
2 (μ^+ stored and μ^- stored)

Bueno, Campanelli, Rubbia; hep-ph/00050

Simulated distributions for a 10kt Lar detector at L = 7400 km from a 30 GeV nu-factory with 10^{21} μ^+ decays.



Physics Reach



Huber, Lindner & Winter; hep-ph/0204352

Impact of systematic uncertainties (blue), correlations (green), & degeneracies (yellow).

2.6×10^{20} decays/yr $\times$ 8 yrs

$\Delta m_{32}^2 = 0.003$ eV^2 , $\Delta m_{21}^2 = 3.7\times10^{-5}$ eV^2 ,
$\sin^2 2\theta_{23} = 0.8$, $\delta = 0$, $\sin^2 2\theta_{12} = 0.8$

Sensitive to $\sin^2 2\theta_{13}$ down to a few $\times$ 10^{-5}, two orders of magnitude better than expected for high performance superbeams.

Can determine the sign of Δm_{32}^2 provided $\sin^2 2\theta_{13}$ exceeds a few $\times$ 10^{-4}, two orders of magnitude better than expected for high performance superbeams.

If LMA with Δm_{21}^2 in the center of favored region, will be sensitive to maximal CP violation provided exceeds about 10^{-4}. But the sensitivity crucially depends on Δm_{21}^2 .

Studies

US Design Study 1: http://www.fnal.gov/projects/muon_collider/nu-factory/

"The result of this study clearly indicates that a neutrino source based on the concepts presented here is technically feasible. According to our current understanding it will not quite meet the intensity specified & it should probably have an energy lower than originally specified (50 GeV). There is clear indication though that we would & should improve the performance, and also how it could be done … ."

US Design Study 2: http://www.cap.bnl.gov/mumu/studyii/FS2-report.html

Achieved improved design with a factor of 6 increase in intensity compared to the study 1 design.
With a few MW proton source can achieve the goal (2×10^{20} decays / year) for a high performance neutrino factory.

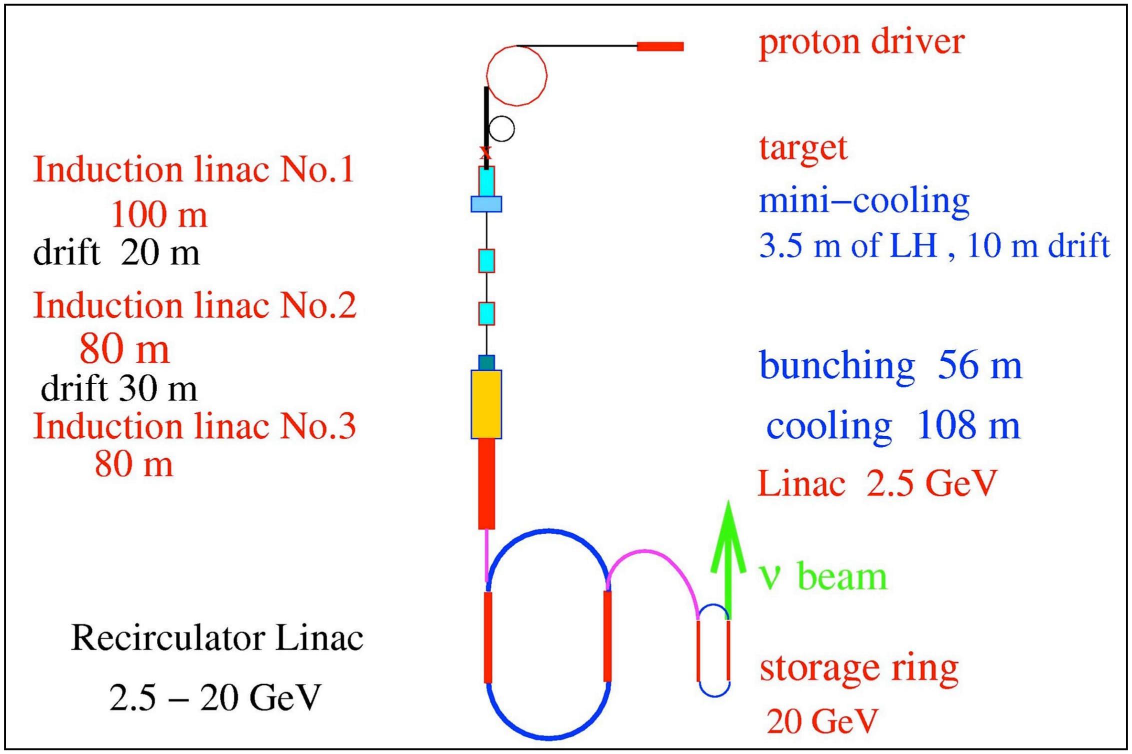
CERN Study: CERN 99-02

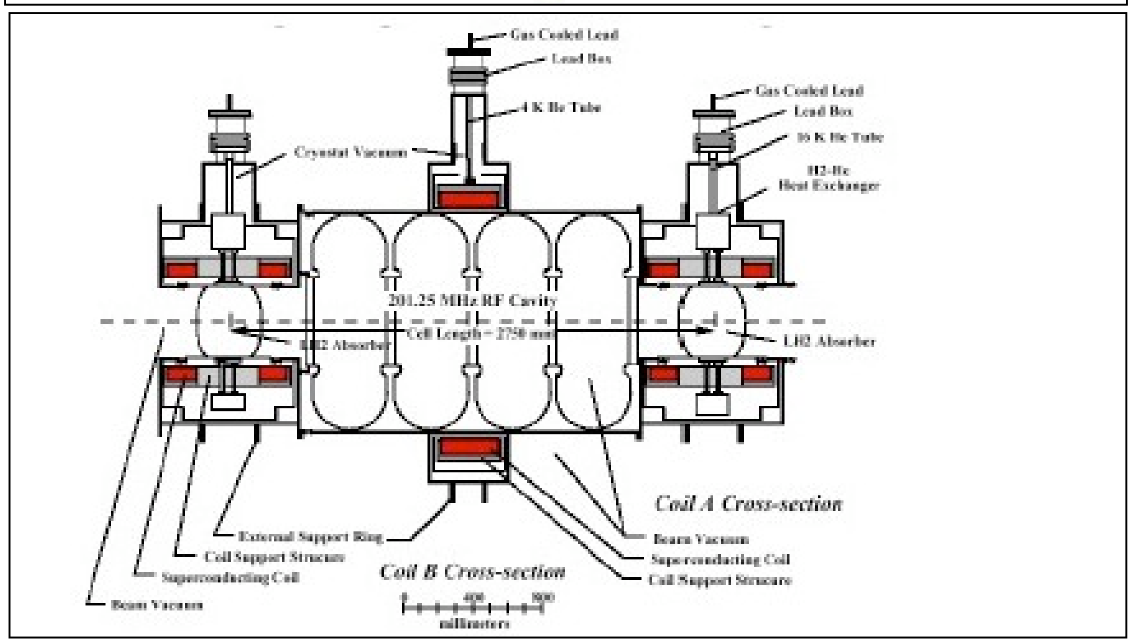
Similar design concept to the US study designs, but different technology choices.
Broadens the technologies being studied, will ultimately lead to a better final design.

Japanese Study: May 2001

Very different design concept (large acceptance accelerators, no cooling channel).

Design





Study 2 design
1.2 10^{20} decays per “snowmass year” per MW protons on target.

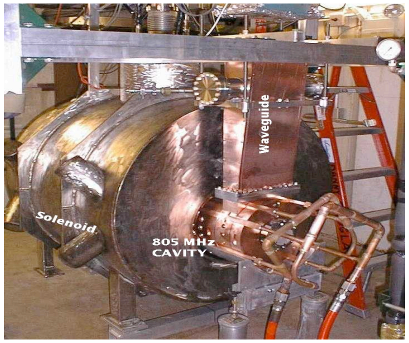
4 MW proton driver
4.8 10^{20} decays/year

Biggest Challenges:

Targetry for 4 MW beam

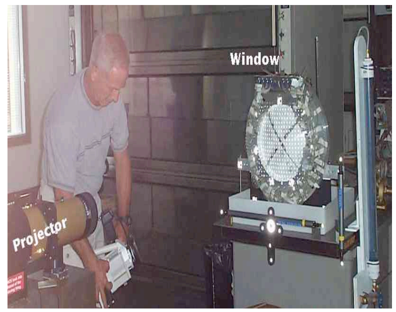
Ionization Cooling Channel

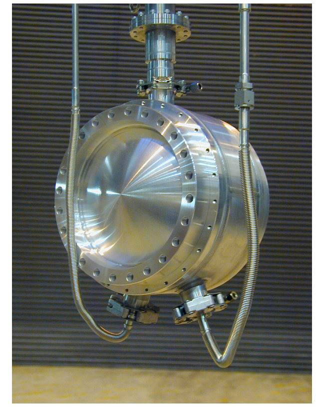
Hardware R&D



5T Cooling Channel Solenoid – LBNL. Open Cell NCRF Cavity operated at Lab G – FNAL

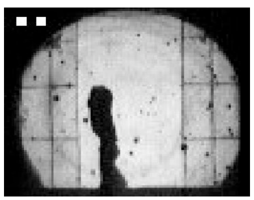
Thin absorber windows Tested – new technique – ICAR Universities



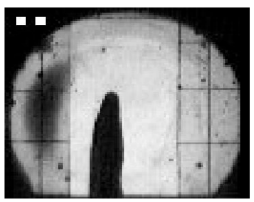


Liq.H Absorber – KEK
To be tested at FNAL

Tested Be-Windows for RF Cavities -- LBNL



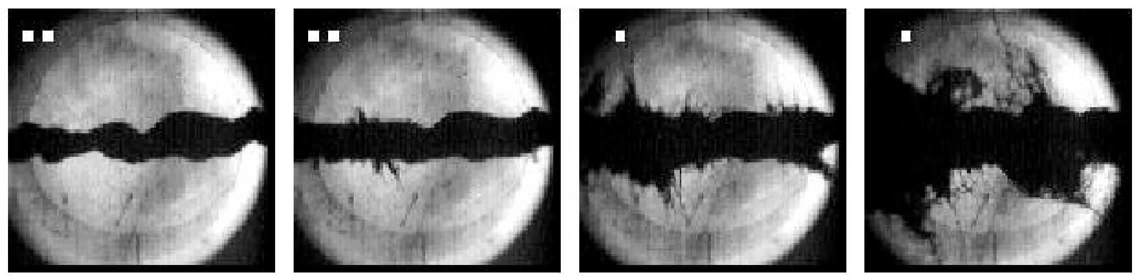
0 Tesla



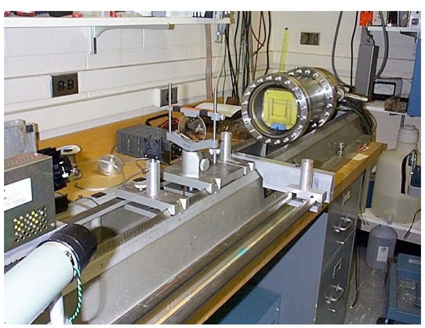
13 Tesla

CERN/Grenoble Liquid Hg jet tests in 13 T solenoid

t | 0.75 ms | 2 ms | 7 ms



BNL E951: Hg Jet in AGS beam

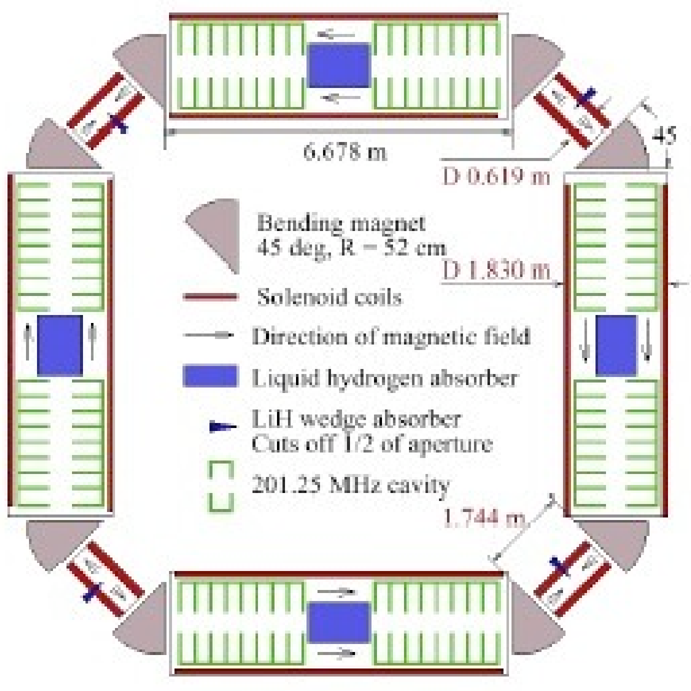


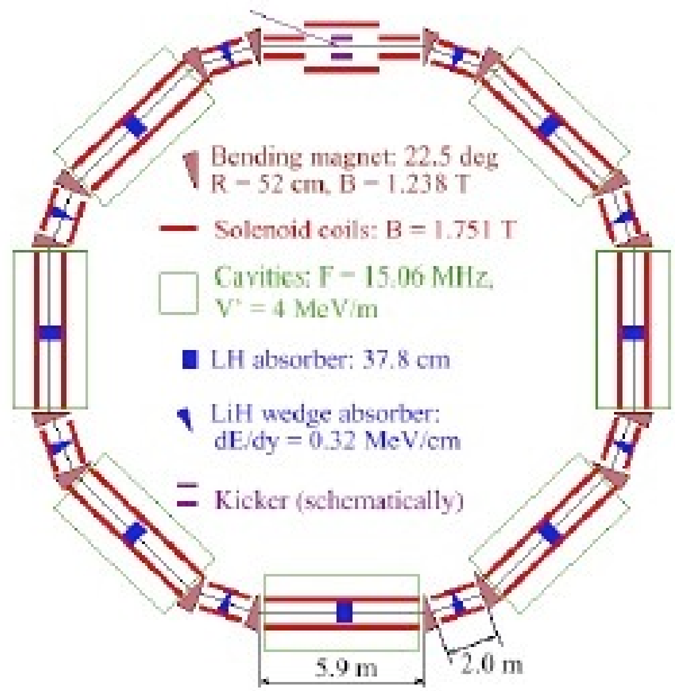
Bolometer detectors for Window Beam profile Measurements – U. Chicago

High-Gradient RF Tests in High Magnetic Field – FNAL

Design Progress

1. 6D cooling theory being developed.
2. Ring cooler designs incorporating emittance exchange now look promising – simulation studies underway cost reduction & path to a Muon Collider ?
3. FFAGs being investigated for acceleration cost reduction ?
4. Phase rotation scheme based on rf cavities being developed cost reduction ?





Technical Review

Most recent (Oct. 01) annual (MUTAC) technical review report (Spring 02) was very positive. The MUTAC report received a strong letter of transmittal from our oversight group (MCOG = representatives from BNL, LBNL & FNAL Directorates):

> “ The impressive record of progress is epitomized by the summary judgement of the report, namely, that *The committee finds the progress since last year excellent*. ”

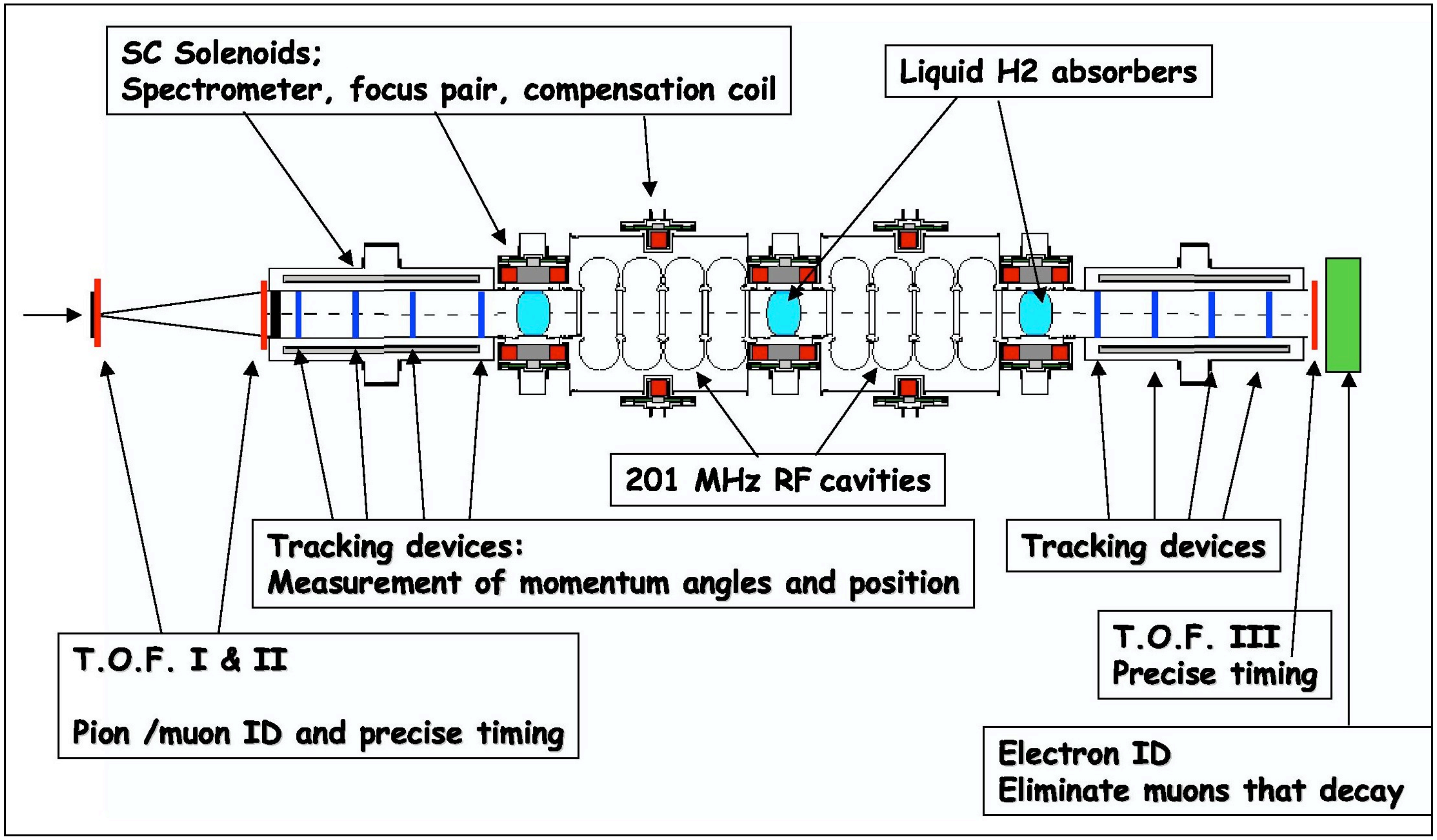
The MUTAC report also states that:

> “The cooling demonstration is the key systems test for a Neutrino Factory ”

MICE

LOI for an International Cooling Experiment presented at PSI and Rutherford Lab

Rutherford Lab has put in place a project team, & is inviting full proposal by end of year.



Single particle concept developed (most recently) at CERN.

World Wide effort now in progress to produce a proposal towards the end of this year.

NSF proposal for support submitted & DOE sister-proposal to be submitted soon.

US: D. Kaplan
Europe: A. Blondel
Japan: Y. Kuno

Status & Prospects

Active □-Factory design & component prototyping in Europe, US, & Japan. R&D pursued by Lab and University physicists … particle physicists & accelerator physicists.

US studies have shown □-Factory feasible after a few (6 – 10 ?) years of well supported R&D. The R&D at present has inadequate support.

CERN & Japanese studies show alternative technology choices may be promising … must be pursued until we are ready to make a choice

The main focus of the R&D in the next couple of years will be to reduce the cost, and demonstrate muon cooling technology (needed to make a very bright muon beam) □ MICE international cooling experiment.

Main Immediate Challenge - Funding

HEPAP sub-panel recommended flat funding for the Neutrino Factory & Muon Collider R&D at the FY01 level.

The DOE support was halved between FY01 and FY02, and then halved again between FY02 and FY03 (guidance).

Present funding level inadequate to support a viable hardware R&D program … although the momentum of, & enthusiasm within, the collaboration should see us through FY03 … but not FY04 unless we can reverse the funding trend.

To reverse the trend in FY04 the next few weeks are critical.

Opportunities

Present contributions of the LBNL beams group are central to the R&D program … and get good exposure.

I believe that any participation of particle physicists, even only at the level of participating in meetings and giving advice, would enhance the LBNL activity.

Best would be participation of a particle physics postdoc or student (great training ground) :

- GEANT/ICOOL simulation studies
- MICE experiment
- benchtop hardware activities (e.g. rf cavity R&D)

… Plus lots more, including continued studies exploring the physics program at a Neutrino Factory.